trans-GZK Cosmic Rays: Strings, Black Holes, Neutrinos, or all Three?

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We review the scenario in which "strongly interacting neutrinos" are responsible for inducing airshowers with inferred energies $E > 8 \times 10^{19}$ eV. This possibility arises naturally in string excitation models having a unification scale effectively decoupled from the Planck scale. We then show that phenomenological quantum gravity considerations reveal an equivalency of "mini-black hole" and strongly interacting neutrino pictures for explaining trans-GZK events. This equivalence can be exploited to predict single particle inclusive distributions. The resulting observable consequences in airshower development are studied using the Adaptive Longitudinal Profile Shower (ALPS) simulation.

1. INTRODUCTION

The publication of the seminal papers by Greisen and Zatsepin & Kuzmin [1] predicting the energy attenuation of protons overs tens of megaparsecs due to interactions with CMB photons (GZK effect), together with the observation of cosmic ray airshowers with inferred energies of $\gtrsim 10^{20}$ eV, has created a vigorously pursued area of particle astrophysics. In fact, as of 2004 there are many more papers proposing explanations for the existence of these trans-GZK airshowers than there are recorded events! Due to this relatively sparse sample of events, open questions include the existence of statistically significant clustering/anisotropy, correlations with known astrophysical source distributions (e.g., QSOs), the composition/charge of the primaries, and whether the production mechanism is top-down or bottom-up. The present paper, delivered at the 2004 Cosmic Ray International Seminar (CRIS 2004), summarizes a bottom-up scenario whereby the primary incident on the Earth's atmosphere is a neutral, non-hadronic particle such as a neutrino that generates a hadron-like airshower due to the primary interaction being above a low-scale unification threshold. Further details concerning the theoretical considerations sketched here, additional figures and tables, and more complete bibliographies can be found in the referenced papers.

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2. THEORETICAL MOTIVATIONS

If trans-GZK events originate from sources farther away than $50 - 100$ Mpc, the most likely candidate for the primary is some type of neutral particle. A Standard Model neutrino can propagate over cosmological distances with little energy loss, but, of course, the interaction cross-section $\sigma_{\nu N \to \ell X}$ is several orders of magnitude too low to generate the observed showers. However, it has been conjectured for some time that perhaps a "strongly interacting neutrino" could exist due to some as yet undiscovered "new physics", and thus possess the required interaction strength at the appropriate CM energies [2]. With the realization that higher-dimensional string theories may allow interaction unification at energies many orders below the standard 4-dimensional Planck scale of $\sim 10^{19}$GeV [3], interest in the strongly interacting neutrino picture has been revived, and has resulted in new work involving rigorous theoretical

considerations within the framework of a specific model [4]. Additional features relative to cosmic ray airshowers have been extracted, although ongoing work continues to refine the predictions relative to conventional airshower observables [5].

2.1. Review of the String-inspired Scenario

More specifically, if the CM energy of the neutrino-nucleon is above a "low energy" unification scale, the neutrino-quark interaction is "strong", and a leptoquark resonant state can form, $\sigma_{\nu N\to LQ\mathrm{res}\to\ell X}$. In establishing model properties using the phenomenology of higher-dimensional string theories, it is worth noting that "typical" tree level amplitudes for strings yield a cross section that is too small to account for the trans-GZK events [6]. This does not rule out the present model, but does emphasize that weakly-coupled string theories are inadequate here, and one must calculate with the strongly-coupled theory (and non-perturbatively when possible). This is analogous to attempting to calculate quark interactions using QCD.

The basic building blocks of the model are unitarity of the S-matrix, a rapidly (exponentially) rising level density of resonances, unification of interactions with strength $\sim$ Standard Model strong interaction at string scale M_*, and duality of resonances in a given channel with Regge exchanges in crossed channels. Express the total cross section in terms of partial waves and absorption coefficients using the optical theorem,

$$\sigma_{\nu q\to LQ\mathrm{res}}(s) = \frac{8\pi}{s}\sum_{j}^{N_0(s)}(2j+1)(1-\eta_j\cos(2\delta_j)).$$

Note that as s increases, the resonances are no longer purely elastic with absorption slowing the growth of the total cross section, and where $N(s)$ is the resonance level and equals the maximum angular momentum; ignoring corrections $O(M_Z/M_*)$, $\sigma_{\nu q\to LQ\mathrm{res}}$ tends to a constant value. The level density of resonances is well represented for the first few resonances by

$$dN_0 \propto 1.24N_0 \approx \exp 1.24(s_0/M_*^2) \ .$$

2.2. Strings and Quantum Black Holes

A connection between string theories and quantum black holes is not a new idea, and there is notable recent work in this area [7]. Extending this to the case of interest here, Domokos & Kovesi-Domokos have demonstrated a non-perturbative equivalence of the string excitation model with that of quantum "mini black holes" [8].

The treatment in reference [8] is based on a statistical mechanical analysis of the previously introduced string model beginning with consideration of the microcanonical density matrix of the final state,

$$\rho = \sum_\alpha |N,\alpha\rangle\langle N,\alpha|\delta(e-NM_*) \ .$$

A straightforward manipulation yields the standard passge to the canonical ensemble with well-defined entropy S and a temperature that asymptotically approaches the Hagedorn temperature, $T_H = M_*/3\pi$. Recall that in modern QCD, the Hagedorn temperature T_H is interpreted as marking the deconfining phase transition from the low temperature hadron phase (quark confinement) to the quark-gluon plasma. In terms of modern quantum gravity and string theory, the entropy of a d-dimensional quantum black hole (QBH) equals the string entropy S at $T_{QBH}\sim M_*\sim T_H$. It is straightforward to derive additional relations between S, M_*, T_H, and $R_{Schwarz}$.

The asymptotic estimate then has important consequences in allowing a non-perturbative calculation of the single particle inclusive distribution similar to the statistical mechanical analysis carried out at the tree level for specific string models by Amati & Russo (1999). Naturally, calculated quantities are a function of the number of "extra" dimensions in the model (i.e., the number of dimensions in addition to the conventional 4-dim space-time). Depending on model choices for characteristic scales, the resulting multiplicities can be similar to those expected in reactions initiated by a heavy nucleus [8].

2.3. The Transition from SM to Unified Regimes

Because the string-QBH model must contain resonances with the number of states an exponentially growing function of the resonance mass, there is a (nearly) θ-fcn transition from the SM to the unified regime. However, there is obviously

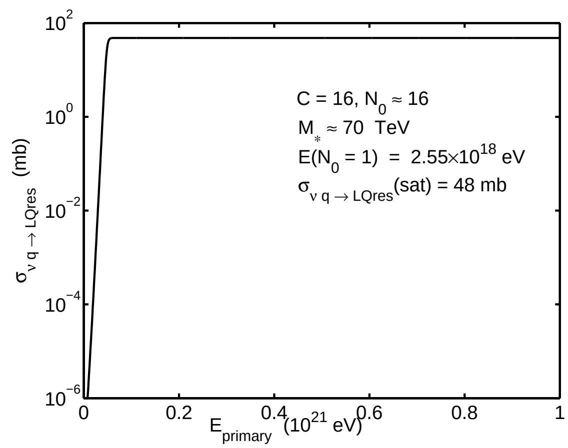

Figure 1. Smoothing function used for transition to unified interactions regime showing the nearly step-function behavior due to the exponentially-rising level density.

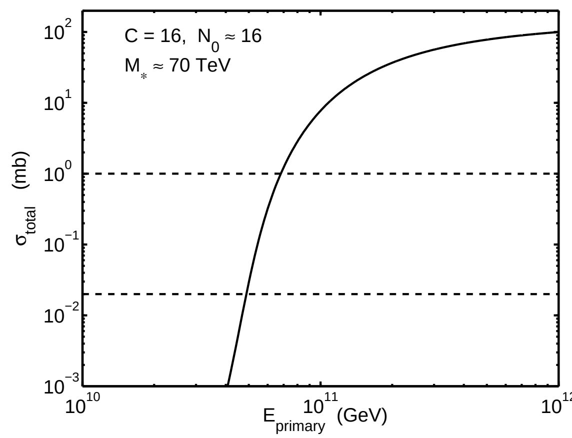

Figure 2. Integration of the approximately step-function neutrino-quark cross section over the appropriate PDFs; the dashed lines indicate the approximate region that would generate observable deep showers.

no exact θ-fcn transition in Nature, thus implying that there must exist a finite width transition region. With no analytic solution describing this transition available from the physics, we choose to treat it empirically by adopting a convenient mathematical smoothing function to represent the neutrino quark cross section. Nevertheless, the chosen form exhibits the desirable physical characteristics of nearly step-function behavior saturating at a TBD strong interaction strength while remaining continuous and without violating unitarity,

$$\hat{\sigma}_{\nu q \to LQ\mathrm{res}}(s) = \frac{16\pi}{M_*^2} \frac{C \exp 1.24 N_0}{1 + \frac{s}{M_*^2} \exp 1.24(N_0 - \frac{s}{M_*^2})} \theta(s - M_*^2).$$

In the above, the conversion from the Lab frame to the CM frame is via $s = 2m_{Nuc}E$, and $N_0 = 2m_{Nuc}E_0/M_*^2$ such that at $E = E_0$ we have $\hat{\sigma}_{\nu q \to LQ\mathrm{Res}}(E = E_0) = \frac{1}{2}\hat{\sigma}_{\nu q}(saturated)$. The choices of C and N_0 determine the value of $\hat{\sigma}_{\nu q}(saturated)$, taken here to be $\sim 50 - 100$ mb. A typical example is shown in Figure 1 for a string scale $M_* \approx 70$ TeV. Of course, the neutrino-quark cross section must be integrated over the parton distribution functions (PDFs) of the participating partons in the nucleon to arrive at the final (observed) quark-nucleon cross section,

$$\sigma_{\nu q \to LQ\mathrm{res} \to \ell X}(s, M_*, N_0) = \int_{\frac{M_*^2}{s}}^{1} dx f(x) \hat{\sigma}(\hat{s}),$$

for $\hat{s} = xs$ and momentum fraction x. The integration is over valence quarks only since there are no leptogluons in current string models, and the sea quarks contribute primarily around $x = 0$. Figure 2 shows the result of integrating the $\hat{\sigma}_{\nu q \to LQ\mathrm{res}}$ of Figure 1 using the CTEQ6 PDFs. There is a region where the cross section would give rise to deep showers, and this is indicated (approximately) by the dashed lines in the figure (this is further discussed below).

3. OBSERVABLE CONSEQUENCES

Thus, as developed in the previous Section, the strength and properties of the unified interaction can lead to a hadron-like airshower initiated by a specific neutral string/QBH state (here taken to be a neutrino), but with some potentially observable differences compared to those generated by hadrons or nuclei. We study the generated

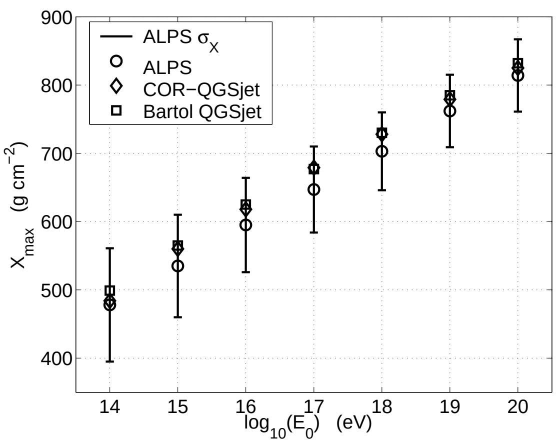

Figure 3. Comparison of X_{max} values generated by ALPS, CORSIKA-QGSjet, and the Bartol-QGSjet simulations for proton primaries. The error bars shown are from ALPS.

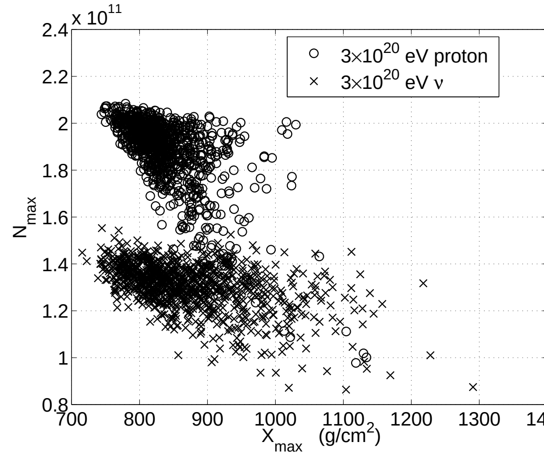

Figure 4. ALPS simulations of 1000 airshowers generated by 3×10^{20} eV protons and (strongly interacting) neutrinos.

airshower properties using the Adaptive Longitudinal Profile Shower (ALPS) simulation originally created by P. Mikulski [9]. ALPS is similar to other hybrid simulations that use subshower parameterization instead of tracking every individual particle. Its performance is comparable to CORSIKA-QGSjet and the Bartol-QGSjet Hybrid Simulation, as shown in Figure 3 for average X_{max} values generated by proton primaries as a function of primary energy. Similar results hold for N_{max} values.

Using the same string model parameters leading to Figures 1 and 2, Figure 4 presents ALPS results showing that, in general, a proton will produce more electrons in a given airshower than a strongly interacting neutrino of the same energy although the depth at maximum electron production is quite similar. The reason for the N_{max} difference is that a larger number of prompt leptons (mostly muons) are produced by the neutrino. However, from Figure 5, it is also seen that a 4.5×10^{20} eV neutrino has both the approximately same X_{max} and N_{max} distributions as the 3×10^{20} eV proton, so that it would be virtually impossible to distinguish airshowers generated by one or the other. In these cases, an additional airshower observable such as muon number

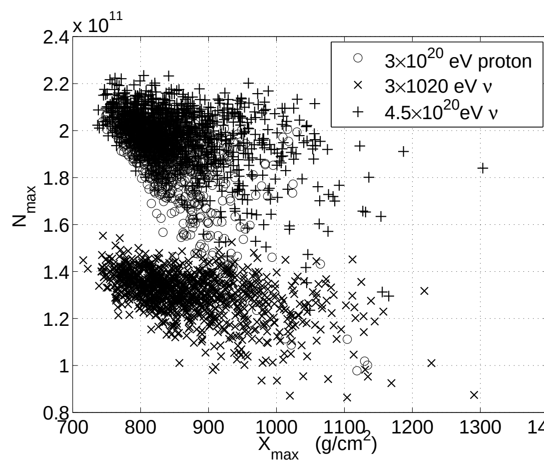

Figure 5. ALPS simulations of 1000 airshowers generated by 3×10^{20} eV protons and (strongly interacting) neutrinos and 4.5×10^{20} eV neutrinos. The higher energy neutrino events ('+' symbols) populate essentially the same region as the proton events ('o' symbols), and are not easily distinguished in this plot.

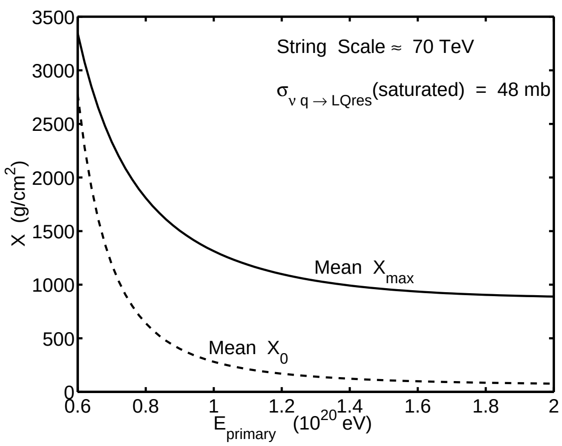

Figure 6. Preliminary extrapolations from ALPS simulations for the variation of X_{max} and X_0 in the SM $\rightarrow$ unified transition region for a 70 TeV string scale.

is required. Still, since it is expected that sources possess a non-monoenergetic injection spectrum, over a large number of observed events with different primary energies, the best discriminator may be identification of a specific source candidate since the source distance can eliminate protons as candidate primaries.

Another possible discrimination technique is the observation of highly inclined or nearly horizontal airshowers since the expected width of the SM $\rightarrow$ unified transition region should produce an excess of observed showers relative to that expected from protons alone. Predictions (extrapolations) for how X_{max} and X_0 scale with the changing cross section in the transition region are shown in Figure 6. Also note that the fluctuations around the mean values shown in Figure 6 also increase very rapidly with decreasing cross section. The interesting point here is that an observed flux of inclined showers can be used to directly constrain the string scale, and, depending on the model favored by Nature, this may be the *only* way to do this in the next decade (or beyond).

4. DISCUSSION AND SUMMARY

It should be mentioned that the idea that mini black holes might be produced in extra-dimensional theories with energy scales orders of magnitude lower than the Planck scale has been explored previously by several authors [10]. However, the model presented here differs in several important aspects:

1. "TeV-Scale Gravity is set by the SM electroweak scale (EW),
2. Interactions are not unified in such models (not a GUT), so there are no strong scale interactions,
3. The cross sections for the black hole interactions are derived using a semi-classical approach utilizing geometric total cross sections, $\sigma_{BH} \sim \pi R^2_{Schwarz}$, and resonances are not included; while these cross sections are considerably enhanced compared to SM EW values, they are still significantly smaller compared to SM strong cross sections.

Currently, experimental results do not rule out the model discussed here, TeV-scale gravity models, or many other competitors. However, the next generation detectors, especially Auger and ASHRA, that are nearing completion are quite capable of discrminating among the possibilities.

It is also interesting to note that a detailed analysis of the AGASA data appears to indicate that the highest energy cosmic rays with $E > 8 \times 10^{19}$ eV may be distributed on the sky differently than those having energies $4 < E < 8 \times 10^{19}$ eV, and this may support the idea that the highest energy airshower events are generated by neutral particles that have propagated distances in excess of 100 Mpc [11]. The main difficulty with such a scenario is that, at this time, it is difficult to understand how a $\gtrsim 10^{20}$ eV neutrino is produced without first generating a $\sim 10^{21} - 10^{22}$ eV hadron, and it is simply not known if such an astrophysical engine exists. However, it is probably too soon to say with absolute certainty that such sources cannot exist.

Finally, we summarize the main points presented here. Our work is continuing in both the theoretical and the simulation areas, and will be

reported in future papers. The robust features of the string/QBH phenomenology developed up to now include the following:

1. For given values of C and N_0, the width of the SM $\rightarrow$ unified transition region broadens as the characteristic string scale M_* increases, independent of the choice of smoothing function; a lower limit on the flux of deep showers corresponds to an upper limit on M_*,

2. The energy at which the rising cross section reaches 1/2 the saturated unified value determines the presence (or lack) of a dip at high energies in the CR spectrum,

3. Exploiting the String-QBH equivalence provides a non-perturbative method for calculating single particle inclusive distributions,

4. The presence of extra dimensions affects the single particle inclusive distributions in a way that is potentially observable in cosmic ray air-showers, and may provide a mechanism for determining the number of extra dimensions preferred by Nature.

The model also yields a natural way to include an additional component in the EHECR distribution if protons, pions, and neutrinos are produced in astrophysical engines with proton propagation limited by the GZK effect, but with neutrinos able to propagate over cosmological distances.

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